

Short communication
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Climatology of geostrophic currents in the Northern Adriatic

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Climatology of the geostrophic currents in the northern Adriatic, based on a large amount of historical data, is documented. The geostrophic circulation can be resolved into the winter circulation, the summer circulation and transition circulations in spring (April and May) and in autumn (September and October). There is a permanent existence of a local cyclonic gyre in Trieste Bay and a northern Adriatic (NAd) current connected with western-middle Adriatic (W-MAd) current throughout the year. During the winter period the circulation in the northern Adriatic is a part of the global Adriatic cyclonic gyre. In the spring starts the meandering of low-salinity water toward the east. This anticyclonic meander comes to the Istrian coast in August and September in conjunction with the Istrian coastal counter-current (ICCC), suggesting the existence of a sharply defined eastward moving anticyclonic meander from June to September. There is good agreement in August and September between measured residual and calculated baroclinic currents. The northern Adriatic (NAd) cyclonic gyre is present only in December.

Keywords: climatology, geostrophic circulation, baroclinic current, northern Adriatic

Introduction

The global circulation of the Adriatic Sea is generally cyclonic and was first established by Voss in 1677. This cyclonic gyre was later confirmed by analyses of geostrophic currents (*e.g.* Zore, 1956, Mosetti and Lavenia, 1969, Limić and Orlić, 1986). It was considered that there is also a cyclonic gyre in the northern Adriatic. The cyclonic gyre to the area east of the Po river delta was described by Mosetti and Lavenia (1969).

Zore-Armanda and Vučak (1984) analyzed current-meter data collected in the northern Adriatic and suggested a scheme of residual circulation with

a cyclonic gyre north of the Po river delta – Rovinj line and an anticyclonic meander south of this line.

Orlić (1989) proposed two schemes for surface circulation in the northern Adriatic, one for the spring-summer period and the second for the autumn-winter period, based both on literature and qualitative analyses of hydrographic and current-meter data. The same conclusion was reached by Brana and Krajcar (1995). According to these two patterns of circulation, the northern Adriatic is included in the global Adriatic cyclonic circulation only in the cold part of the year. The cyclonic gyre north of the Po river – Rovinj line is present throughout the year and is larger in summer period than in the winter.

The results of direct current measurement showed the possibility of the existence of a large cyclonic gyre in the northern Adriatic (Cerovečki at al., 1991, Brana and Krajcar, 1995). Over the years of measurements the dominant direction of residual currents west of Pula was north and northwest, although at the end of summer and beginning of autumn there was a typical southeast direction of residual currents, so the authors proposed an anticyclonic circulation in this period of inverted current (called an inversion period). Supić at al. (2000) demonstrated the existence of a southeastward surface current named Istrian Coastal Countercurrent (ICCC) which usually appears in August along the Istrian coast line and runs counter to the general Adriatic-wide cyclonic flow. It seems that a high intensity of the ICCC coincides with oceanographic conditions (closed circulation in the area) which favor near anoxia or mucilage events observed in the northern Adriatic (Supić at al., 2003a, 2003b).

The existence of cyclonic gyre north of the Po river delta – Rovinj line was not confirmed in the work of Artegiani at al. (1997a, 1997b). They analyzed hydrographic data collected in the Adriatic sea during 1911–1914 and 1947–1983 and reconstructed the mean seasonal anomaly of dynamical depth (for four seasons) relative to the 30 and 140 dbar surfaces in the Adriatic sea.

In this work the climatology of the geostrophic currents in the northern Adriatic, based on hydrographic data collected in the area during the 20th Century, is documented. There is large overlap of hydrographic data used in this work (Mediterranean Hydrographic Atlas data base (MEDATLAS)) and in the work of Artegiani at al. (1997b). However, here are added hydrographic data collected by Center for Marine Research (CMR) »Ruder Bošković« Institute at Rovinj and the monthly temperature and salinity fields are estimated for every month using a new method of eigen functions (Krajcar, 2003). From the estimated monthly mean fields of temperature and salinity the geostrophic climatological fields were reconstructed and compared with residual currents derived from direct current measurement.

Data and methods

At the station SJ209 ($44^{\circ} 47.5' \text{ N}$, $13^{\circ} 29.8' \text{ E}$) located 15 Nm west of Pula a large amount of current-meter data during the period 1985–1993 was collected. During this period there were a total of 35749 hours of measurement at the surface and 37158 hours of measurement at the bottom. The tidal and inertial signal was extracted from the hourly values of u (eastern) and v (northern) current components and then the daily mean values were computed. In the next step a mean annual cycle, standard errors of the mean and standard deviation of residual currents were determined by multiple regression fitted to the first six annual Fourier harmonics.

In this work were used temperature and salinity data collected by CMR Rovinj up to September 1998. From this data base was selected the subset of data from 45 stations with more than 12 measurements of vertical profile

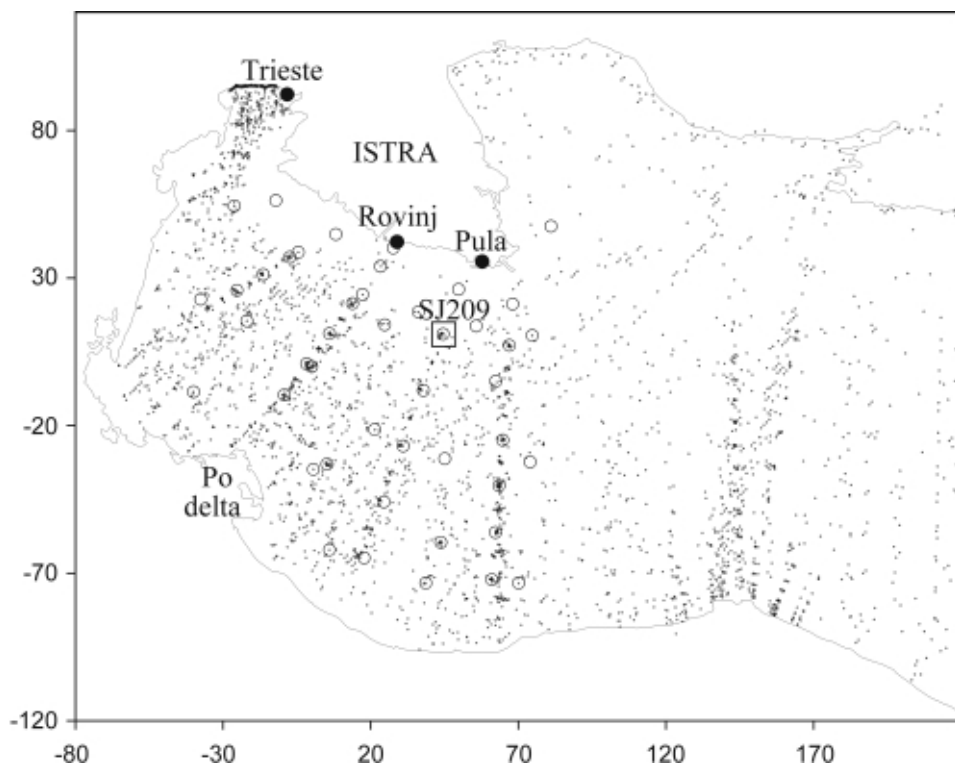


Figure 1. Northern Adriatic area included in the analysis. The origin is at 45° N , 13° E , the x coordinate is in the SE direction and the y coordinate in the NE direction expressed in km. Dots represents Medatlas data, circles CMR stations. The circle inside square is station SJ209.

(Figure 1). There was a total of 20970 temperature and salinity data from 4290 vertical profiles.

In the MEDATLAS data base are historical hydrographic data collected mainly with classical methods (bottles) and recently by conductivity-temperature-depth (CTD) probe. Only the data measured in the northern part of the Adriatic Sea are included in the analyses. There were 2848 vertical profiles (bottles) and 1774 CTD profiles (Fig. 1).

The temperature and salinity data from CMR and MEDATLAS data bases were analyzed using multiple regression and principal component analysis (PCA), and climatological temperature and salinity fields for every month were determined as the superposition of terms of the form $g(x,y)h(z)f(t)$ where $h(z)$ and $f(t)$ were orthogonal eigen functions determined from all the data as explained in Krajcar (2003).

After the determination of monthly climatological temperature and salinity fields the density fields and dynamical height fields relative to the 30 dbar surface were calculated in the standard way. The eastern coastal area was excluded from calculations because of the presence of many islands and small amount of data.

Results and discussion

Using a complex method for the estimation of climatology of temperature and salinity fields it has been possible to reconstruct the climatology of relative baroclinic geostrophic currents with temporal resolution of one month and spatial resolution of about 20 km.

The climatology of relative baroclinic general circulation fields for every month is shown in Figure 2. The general geostrophic circulation in the northern Adriatic consists of four different patterns of circulation in four seasons. The first, winter season, includes the period from November to March – a total of five months. The second, a spring season includes April and May. The third is the typical summer season including June, July and August, and finally the fourth autumn season that includes September and October.

The area of Trieste Bay and north of the Po delta – Rovinj line is shallow, with only a small part deeper than 30 m. These shallow areas were not included in the investigated area, but the circulation could be extrapolated to the cyclonic gyre as indicated in Fig. 2, in accordance to earlier works (*e.g.* Zore-Armanda et al., 1995).

The Bora wind is frequent in the winter period and generates an anticyclonic gyre in the climatological residual current fields (*e.g.* Zore-Armanda et al., 1995; Beg Paklar et al., 2001) although at the same time there is no anticyclonic gyre in the geostrophic current field (thermohaline origin) in winter as is suggested in Fig. 2 for the winter period.

In the winter period (from November to March) the anticyclonic gyre south of the Po – Rovinj line is not present, except for the northern Adriatic

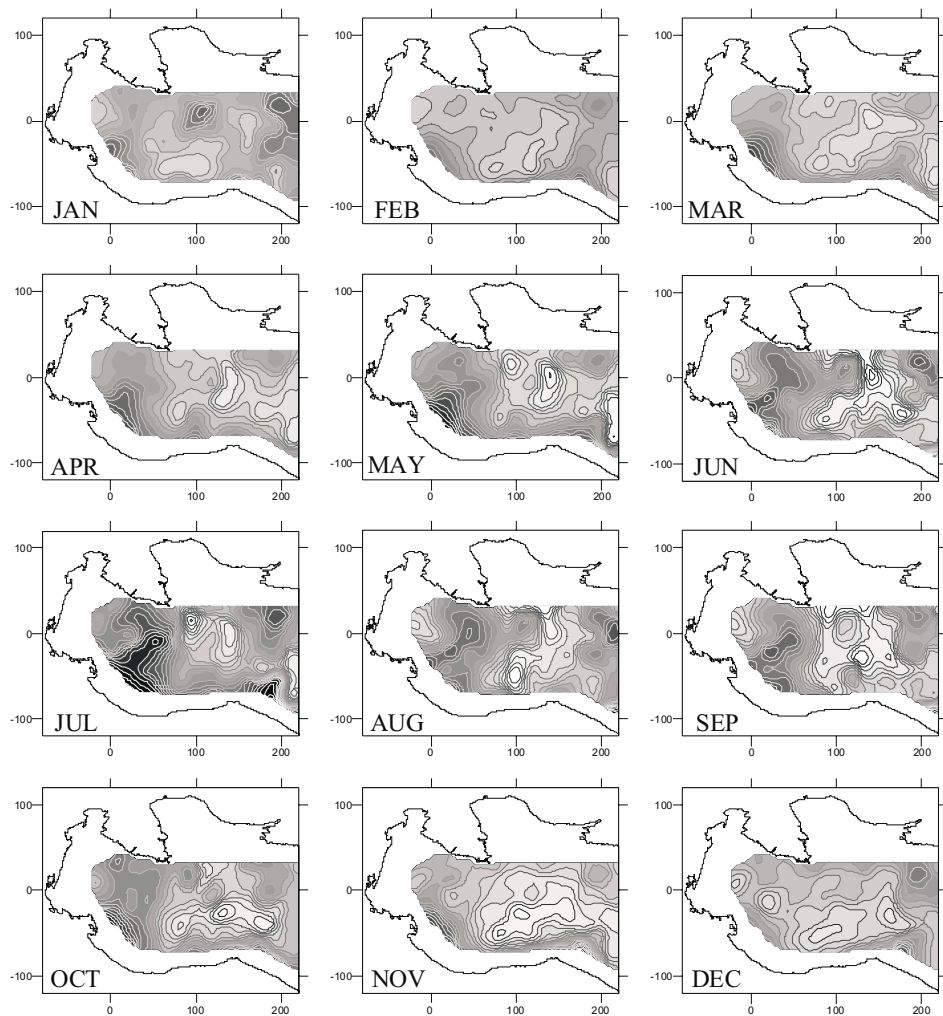


Figure 2. The climatology of geostrophic currents in the northern Adriatic. Dynamic heights at the sea surface relative to the 30 dbar surface are presented. The contour interval is 2 dyn mm. Cyclonic flow is around brighter areas while anticyclonic flow is around darker areas. The x-scale (in km) is the SE direction, the y-scale in the NE direction and the origin is located at 13° E, 45° N.

current (NAd current, Artegiani et al., 1997b) flowing down the Italian coast. In this work NAd current is present throughout the entire year and is continuously connected with the western-middle Adriatic current (W-MAd current). In the spring (April and May) starts the meandering of low-salinity water from the Po river delta towards the east. This process continues in the summer period (June, July and August) and the anticyclonic meander comes

to the Istrian coast. In the summer period cyclonic and anticyclonic gyres and meanders in the northern Adriatic area are present indicating the complex structure of the circulation in this period.

From the analysis of oceanographic data collected by expeditions of *Najade* and *Ciclope* in the period 1911–1914., Zore (1956) obtained geostrophic currents of a southerly direction in the area of station SJ209 (for measurements from 16 August to 6 September 1911). This pattern of circulation is confirmed here at the climatological scale. In August and September an anticyclonic gyre near the Istrian coast is clearly visible as a part of an anticyclonic meander that starts near the Po river delta. August and September are the months of the so called inversion period – the period of ICCC development. In autumn (September and October) the low-salinity water accumulated during spring and summer is transported via the ICCC that flows down (southerly direction) the Istrian coast and then south-west towards the Italian coast and finally merges with the W-MAd current.

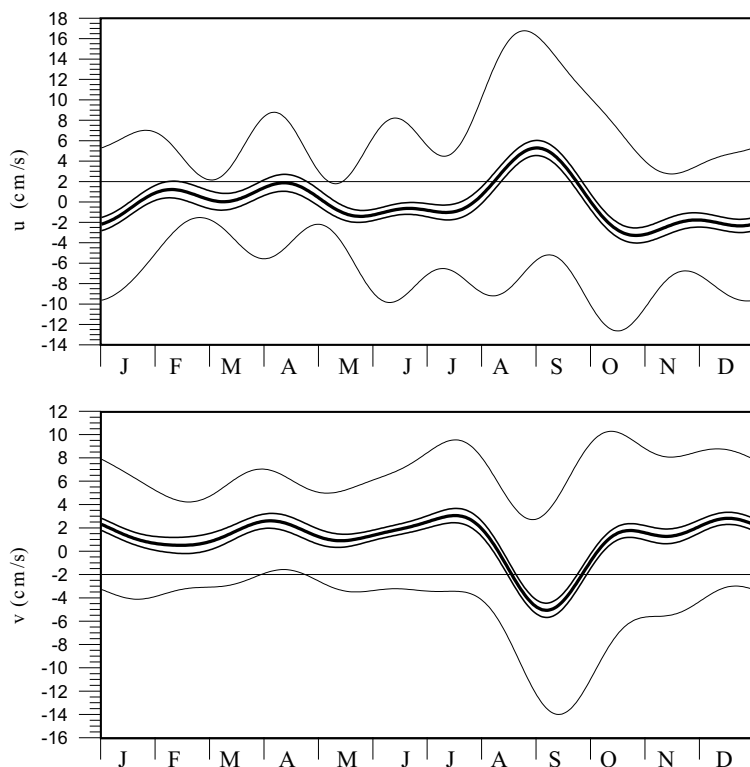


Figure 3. The annual cycle of the residual surface currents at station SJ209. The thick line is the estimated annual cycle of mean residual u (upper pannel) and v (lower pannel) components, medium size lines represent the standard error range of the estimated mean, and thin lines are the standard deviation range.

In November the winter cyclonic pattern of circulation starts again with a very strong NAd current. In December a developed local northern Adriatic cyclonic gyre is present (autumn period as defined by Artegiani et al., 1997b).

The annual cycle of residual surface currents at station SJ209 is presented in Figure 3. Throughout the year the direction of the residual current is towards North North West with the exception of August and September with a strong current directed to the southeast. August and September are months that rarely experience strong wind (Bora or Sirocco), so the residual current during these months is mainly of thermohaline origin, in good agreement with earlier reports (*e.g.* Supić et al., 2000, 2003a, 2003b; Brana and Krajcar, 1995) and with climatological fields of geostrophic current presented here. There is very good agreement between surface residual current (derived from current-meter time series) and the baroclinic component of geostrophic current at station SJ209 during August and September. There is a difference in velocity of less than 0.5 cm/s (the mean velocity in this period is about 4 cm/s), and the difference in direction of about 30 degree or less.

There is also great similarity between the T-shaped geostrophic anticyclonic meander in August and September and the Sea WiFS images of surface chlorophyll-*a* concentration in the northern Adriatic on 19 and 20 September 1997 (Mauri and Poulain, 2001).

There is a continuous, smooth spatial and temporal development of an anticyclonic meander starting in March near the Po river delta, growing eastward and disappearing in October. When this anticyclonic meander reaches Istrian coast the ICCC then develops, although the current-meter data from station SJ209 indicate that this is not a smooth but rather a step-like change from north to south direction in few or only one day. This suggests that there is a sharp edge to the anticyclonic meander with low-salinity water of Po river origin. When this front reaches the station SJ209 then residual current changes direction towards the south-east.

Zore-Armanda et al. (1995, 1996) analyzed current meter data measured at an oil platform in the period 1978–1986, at two fields in the northern Adriatic named IVANA and IKA located south-west of station SJ209. The field IVANA is located near the center of the anticyclonic meander and the residual currents were small in the summer period. The field IKA is in the area of closure of the Adriatic cyclonic gyre with dominant westward direction of residual currents, in good agreement with climatological geostrophic currents in summer.

Conclusions

By the complex method of modal decomposition, climatological temperature and salinity fields in the northern Adriatic were estimated with a temporal resolution of one month and spatial resolution of about 20 km based on

the large amount of hydrographic data collected in the area during the 20th Century and stored in MEDATLAS and CMR Rovinj data bases.

From the estimated temperature and salinity fields the density and dynamical depths relative to the 30 dbar surface fields were calculated using a standard procedure with the same high spatial and temporal resolution. The relative baroclinic component of geostrophic current fields is documented in this work and compared with earlier investigations in the area of the northern Adriatic.

Climatological geostrophic fields show a complex structure of general circulation in the northern Adriatic that can be resolved into four patterns of circulation; the winter circulation (from November to March), the summer circulation (from June to August) and intermediate circulation transitions from winter to summer circulation in spring (April and May) and from summer to winter circulation in autumn (September and October).

Throughout the year a current to the east, north of the Po river delta – Rovinj transect is present and that is probably the southern part of a local cyclonic gyre in Trieste Bay. NAd current is also present throughout the year and is connected with the W-MAd current. During November and December the baroclinic circulation in the Northern Adriatic is a part of the global Adriatic cyclonic gyre, and without any anticyclonic gyre in the area south of the Po delta – Rovinj line. This gyre is present in the residual circulation caused by Bora wind and does not have a thermohaline origin.

In the spring (April and May) the meandering of low-salinity water from the Po river delta towards the east starts. This process continues in the summer period (June, July and August) and the anticyclonic meander comes to the Istrian coast (in August and September), in good agreement with the previously discovered ICCM from the study of hydrographic data measured at the Po river delta – Rovinj transect (Supić et al., 2000, 2003a, 2003b), and with the so called inversion period as determined from analyses of long current-meter time series (Brana and Krajcar, 1995). In addition, there is good agreement with the satellite images of surface chlorophyll-a concentration in the northern Adriatic on 19 and 20 September 1997 (Mauri and Poulain, 2001). Thus, there are four independent sources of data with similar conclusions strongly suggesting the existence of an anticyclonic meander with low-salinity water of the Po river origin in the northern Adriatic during summer and autumn (from June to September). The residual current measured at station SJ209 rapidly changes from a northwest direction to the southeast suggesting that there is sharp edge to the anticyclonic meander that slowly moves towards the east. There is very good agreement between residual current (derived from current-meter time series) and the baroclinic component of geostrophic current at station SJ209 during August and September with a difference in velocity of less than 0.5 cm/s (the mean velocity in this period is about 4 cm/s), and in the direction of about 30 degree or less.

In November the winter cyclonic pattern of circulation starts again with a very strong NAd current and in December the local NAd cyclonic gyre (autumn period as defined in Artegiani et al., 1997b) develops.

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SAŽETAK

Klimatologija geostrofičkog strujanja u sjevernom Jadranu*Valter Krajcar*

Dokumentirana je klimatologija geostrofičkog strujanja u sjevernom Jadranu temeljena na obimnom skupu povijesnih podataka. Geostrofička cirkulacija se može svesti na zimsku cirkulaciju, ljetnu te prijelazne cirkulacije u proljeće (travanj i svibanj) i u jesen (rujan i listopad). Tijekom cijele godine prisutan je lokalni ciklonalni vrtlog u Tršćanskom zaljevu te sjevernojadransko strujanje povezano sa zapadnim srednjejadranskim strujanjem. U zimskom je razdoblju cirkulacija u sjevernom Jadranu dio općeg jadranskog ciklonalnog vrtloga. U proljeće započinje meandriranje zaslađenih voda prema istoku. Ovaj anticiklonalni meandar dolazi do istarske obale u kolovozu i rujnu što je u dobroj vezi s Istarskom obalnom protustrujom što ukazuje na postojanje anticiklonalnog meandra oštih granica od lipnja do rujna koji se kreće prema istoku. U kolovozu i rujnu postoji dobro slaganje između izmjerenih rezidualnih i izračunatih baroklinih struja. Ciklonalni sjevernojadranski vrtlog prisutan je u prosincu.

Ključne riječi: klimatologija, geostrofička cirkulacija, baroklino strujanje, sjeverni Jadran

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